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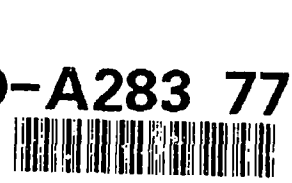

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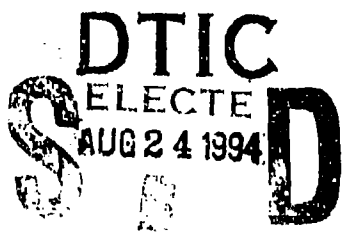
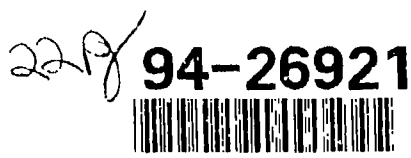
In-Bore Dynamic Response Analysis of a SLEKE I Projectile Fired From the Single Shot Gun (SSG) Railgun

Lawrence W. Burton

ARL-TR-470 July 1994





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U.S. Army Research Laboratory
ATTN: AMSRL-WT-PD
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Recently, Kaman Sciences Inc. experienced an in-bore failure of its Rodman cone projectile design in the single shot gun (SSG) railgun at Maxwell Laboratories as part of the SLEKE projectile program. This projectile design had been successfully launched from a conventional powder gun at axial acceleration levels exceeding those encountered during the electromagnetic (EM) launch which resulted in the failure. As part of the investigation into this failure, an in-bore dynamics code, RASCAL, was utilized to determine the magnitude of the lateral loads encountered. While RASCAL is capable of computing bending and shear responses, it cannot provide detailed stress and strain data through the projectile. What the analysis did show was that for the EM case, the lateral loads were ten times greater than those typical of conventional gun systems and certainly contributed to the cause of failure. A kink in the rail centerline profile was found to initiate large transverse and pitching accelerations of the projectile. Details of the analysis and the ramifications of bore non-straightness on the Rodman cone projectile design are presented in this report.

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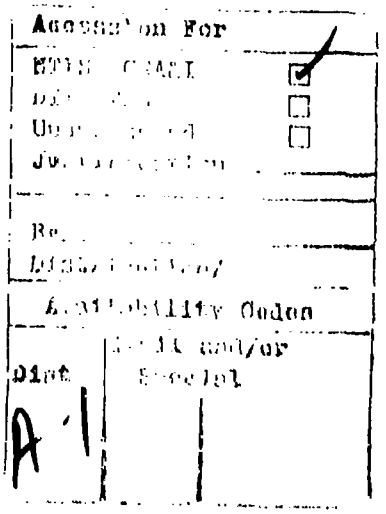

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1. INTRODUCTION

Over the last decade, much effort has been devoted by the U.S. Army ballistic community to gain an understanding of the dynamic interactions between a projectile and gun tube during the launch cycle. Most of this work was motivated by a desire to more accurately fire tank ammunition. This resulted in the development of several gun dynamics codes, as well as utilization of transient three-dimensional (3-D) finite element modeling techniques (Erline and Kregel 1990; Hopkins 1990; Polcyn and Cox 1990; Rabern and Bannister 1990; Wilkerson 1993). An extensive experimental test firing procedure, known as the "jump test," was developed and is now a standard part of any ammunition development program (Schmidt et al. 1990).

During the investigations of conventional tank guns, it became apparent that the profile of the bore centerline played a major role in determining the accuracy performance of a round. It was discovered that large deviations from a true, straight centerline can exist and impart side loads to the projectile which induce balloting and subsequently reduce accuracy. The worst conventional barrel profiles were found to impart 1,000–2,000 g's laterally to projectiles. Such barrels typically had kinks present near their muzzles through which the projectiles would have to travel at relatively high velocities.

During the development of the 120-mm kinetic energy (KE) projectile, XM829E2, the issue of tube straightness and its effects on structural integrity were first studied in some depth. Analysis showed that transverse accelerations of approximately 1,000 g's, even when the applied pressure was much less than peak pressure, can result in large stresses and strains throughout the sabot (Alexander 1989). This was offered as a possible explanation for the random projectile failures which were experienced during the XM829E2 program in test firings from certain gun tubes. Eventually, the manufacturing process for full production tubes was improved sufficiently to minimize bore centerline variations such that lateral loads were reduced.

Recently, the electromagnetic (EM) gun community has begun to express concern over the effects of non-straight barrel profiles or projectiles. However, at this point, the concern is motivated more from the structural integrity standpoint rather than accuracy. The first measurement of an EM gun profile was made in 1991 on the UTCEM Task B railgun. Preliminary analysis based on these data showed lateral accelerations two to three times higher than those which would be expected in typical conventional

cannons (Burton 1993). In retrospect, this may explain why projectile nosetips were observed to be frequently broken off during early EM test firings.

Recently, Kaman Sciences Inc. experienced an in-bore failure of its Rodman cone projectile design fired from the SSG railgun at Maxwell Laboratories. The launch energy of this shot, no. 179, was at full energy—in excess of 8 MJ. The lack of extensive diagnostics has made determining the exact cause of failure difficult; however, this design had survived lower energy shots under equivalent peak axial accelerations, lending credence to the conjecture that bore non-straightness might have a role in the failure. In light of this, an investigation was undertaken to quantify the severity of the lateral loading on the Rodman cone projectile by the SSG railgun and compare it to that for a conventional powder gun. This assessment was made using the RASCAL gun dynamics code (Erline, Kregel, and Pantano 1990) which has been developed to model projectile/gun interaction dynamics in conventional powder gun systems.

2. RASCAL ANALYSIS

RASCAL is a quasi-two-dimensional code which employs beam elements to model both the projectile and gun barrel. The code is labeled "quasi" two-dimensional because it does not couple the effects encountered in the horizontal and vertical planes. The model formulation assumes the projectile contacts the bore at two points with springs. A schematic of the RASCAL projectile model is shown in Figure 1, with variables skff and skgg representing the capability to assign contact stiffness values at the rear and forward boreriders, respectively. Variable spff and spgg provide a means for varying the projectile model wheelbase (that is, the distance between the contacts).

RASCAL was developed to model projectiles with geometrical shapes such as double-ramped KE ammunition or high-energy anti-tank (HEAT) rounds. Kaman's Rodman cone projectile configuration, shown in Figure 2, required some manipulation of the RASCAL geometry modeler. Each beam element was assigned a bending stiffness (defined as elastic modulus times moment of inertia, EI) and equivalent mass. These data were input directly into RASCAL by bypassing the geometry modeler.

Ranges of contact spring stiffness values were analyzed. The lower bound spring value, $k = 1 \times 10^5$ lb/in, was obtained from static push tests conducted at the Army Research Laboratory (ARL) on KE ammunition (McCall and Henry, to be published). The upper bound spring value, $k = 1 \times 10^6$ lb/in, was based on another series of tests performed at ARL (Lyon 1993). An intermediate

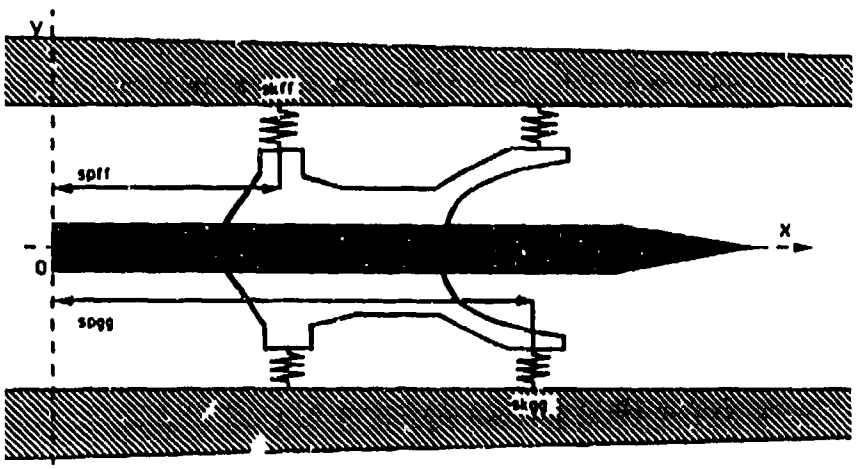

Figure 1. Schematic of RASCAL model spring descriptors.

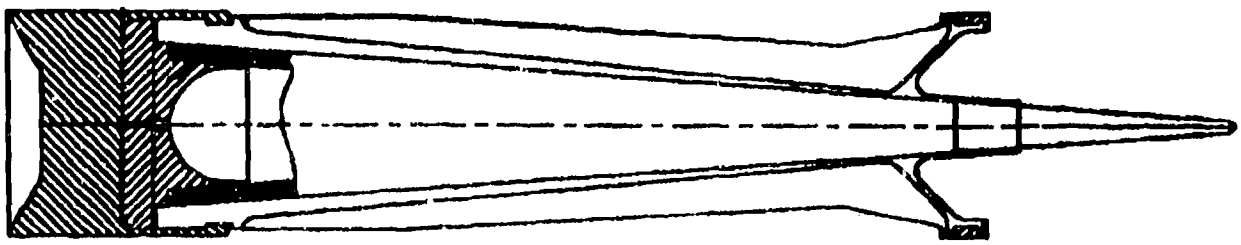

Figure 2. Kaman Sciences Rodman cone projectile configuration.

stiffness value, k = 4.3 × 10^5 lb/in, was also used and was based on previous RASCAL predictions which matched experimental data (Erline 1993). A RASCAL model also requires an interior ballistic model, a bore centerline profile, gun system parameters, and a barrel geometry model. Data for the gun system and barrel models were not available at the time this work was done, so data used in a previous analysis of an EM railgun were employed (Burton 1993). The interior ballistic model is simply projectile velocity vs. time input. The velocity-time data used for the SSG are shown in Figure 3. This velocity profile has a muzzle velocity of 2.4 km/s with a pre-accelerated injection velocity over 400 m/s. These data were based on Maxwell's projections for the Rodman cone projectile, assuming an 8.2-MJ launch energy (Statton et al. 1993).

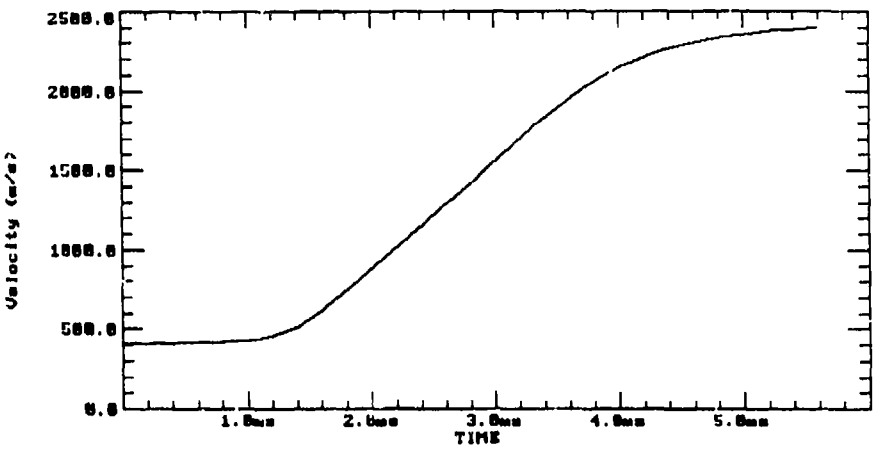

Figure 3. Velocity vs. time plot of Rodman cone projectile from SSG railgun at Maxwell Laboratories.

The SSG railgun bore centerline measurements were made by the U.S. Army Combat Systems Test Agency (CSTA). Measurements were made prior to (September 1) and after (September 16) the in-bore projectile failure. These centerline profiles are shown in Figures 4 and 5, respectively. The insulator profile is denoted by a solid line and the rail profile with a dashed line. It is important to distinguish bore straightness from bore roughness, which is a measure of the consistency of the bore diameter. A bore centerline, or straightness, measurement is made after establishing a reference line-of-sight (LOS) through the center of the bore at the muzzle and chamber ends. An alignment telescope is aimed so that the LOS coincides with the center of a target which is pulled through the tube. Displacements of the target from the reference centerline are recorded at discrete locations along the barrel length (Weddle 1986).

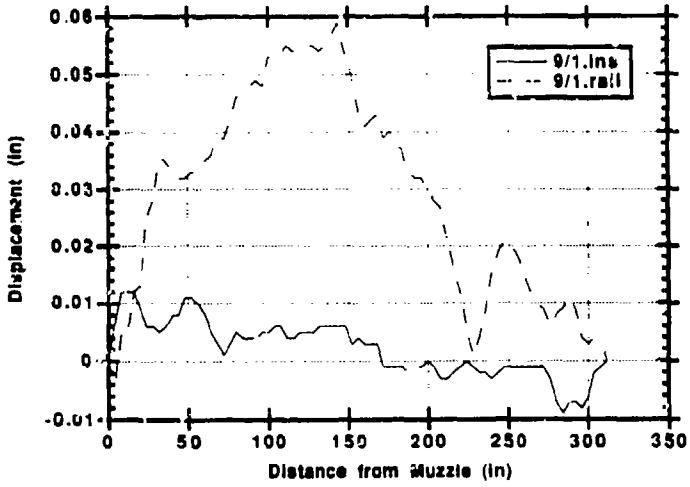

Figure 4. SSG railgun bore centerline profile - September 1, 1993.

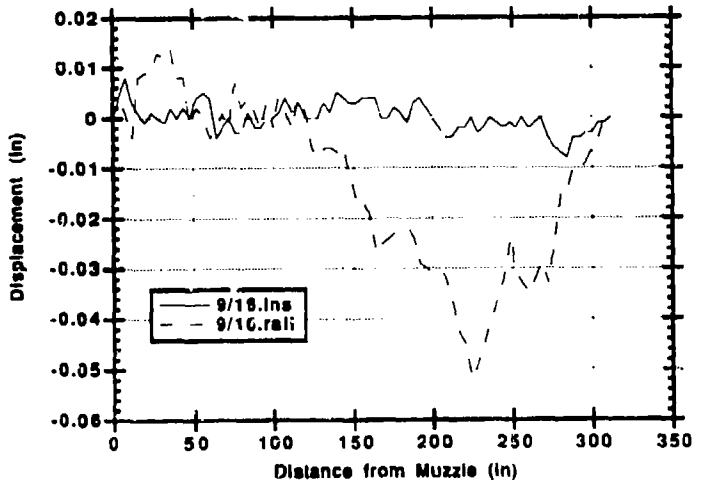

Figure 5. SSG railgun bore centerline profile - September 16, 1993.

Gun system parameters employed in the RASCAL analysis were representative of components from a conventional gun system. The M829, a 120-mm KE round, served as a base line conventional projectile configuration for the purpose of comparison with the Rodman cone projectile results. Further, the centerline profile of a double-travel 120-mm cannon, tube no. 008, and the velocity-time profile for an M829 traversing through it were used to provide a comparison with the EM railgun results. A sketch of the M829 is given in Figure 6, and Figures 7 and 8 show plots of the double-travel centerline and velocity vs. time profiles, respectively.

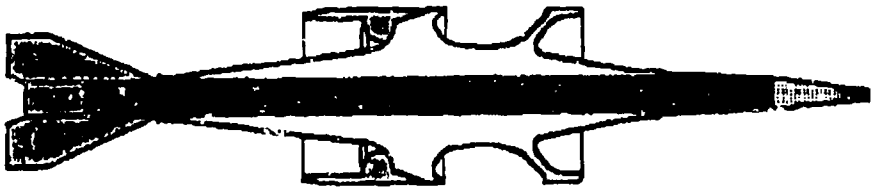

Figure 6. M829 projectile.

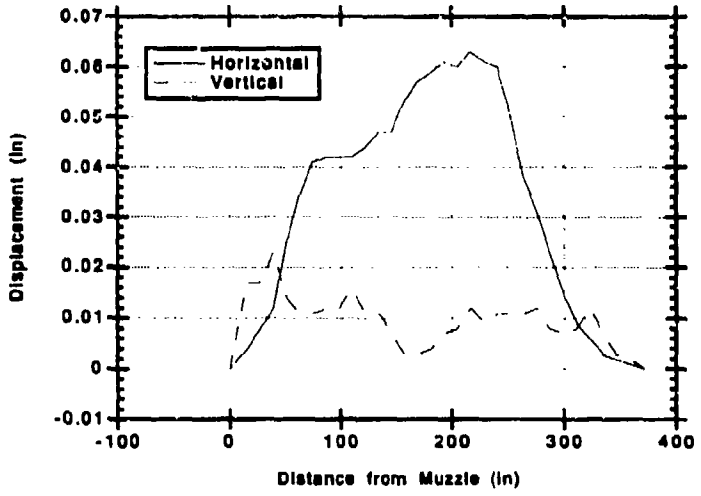

Figure 7. Bore centerline profile of a double-travel conventional cannon.

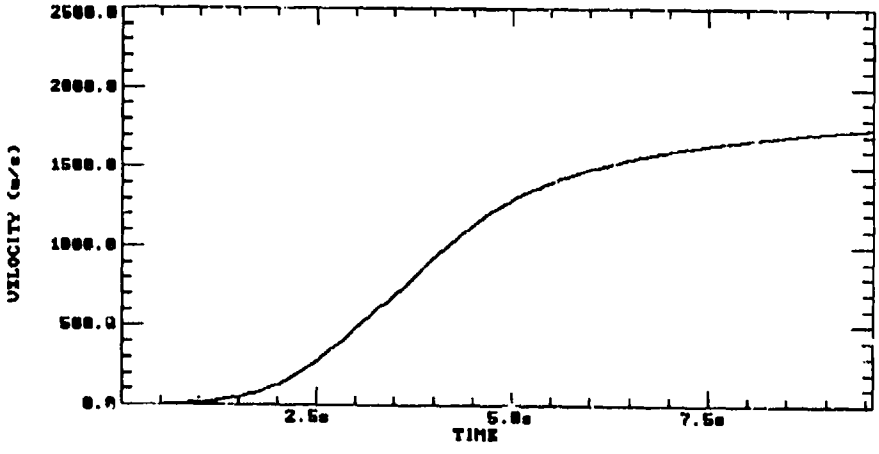

Figure 8. Velocity vs. time history for the M829 projectile.

3. CASE STUDY MATRIX

Seven cases were modeled, spanning three system parameters: bore centerline, projectile, and velocity-time profile. Table 1 lists the seven cases with cases 1 and 2 representing the SSG system prior to (September 1) and after (September 16) shot no. 179, respectively. Cases 3 and 4 concern the effects of velocity-time profile while cases 5 and 6 concern different projectile designs. Lastly, case 7 concerns the base line case of a conventional KE projectile in a conventional gun system and was analyzed to provide benchmark data against which to compare the EM railgun system results.

Table 1. Matrix of Conditions for the Various Case Studies

Case	Centerline	Projectile	Velocity-time profile
1	9/1 rails	Rodman	EM
2	9/16 rails	Rodman	EM
3	9/1 rails	Rodman	Conv
4	9/16 rails	Rodman	Conv
5	9/1 rails	M829	EM
6	9/16 rails	M829	EM
7	DT Conv	M829	Conv

Each of the seven cases was run with the three spring stiffness values assigned to both the front and rear boreriders. In reality, the spring stiffness values will differ between the front and rear boreriders, but lacking any data to determine these differences, the same stiffness value for both contacts was assumed. Thus, a total of 21 RASCAL runs were required to model the 7 cases for each of the 3 borerider stiffness values.

4. RESULTS

Transverse and pitching accelerations were extracted from the RASCAL output. The transverse acceleration at each contact is obtained by taking the time derivative of the beam element velocities at both the front and rear contacts. Likewise, the pitching acceleration is computed from the time derivative of the angular velocity at each of the two contact points.

Table 2 lists the transverse accelerations found for each case and spring stiffness value. The results from each case for the medium spring stiffness value, $k = 4.3 \times 10^5$ lb/in, will be used for purposes of comparison. It is apparent that the SSG bore straightness profile imposes lateral accelerations more than ten times those found in a conventional system (compare cases 1 and 2 vs. case 7 in Table 2). Also note that a change in the velocity profile produces only modest effects on the magnitudes of transverse loadings (compare cases 3 and 4 vs. cases 1 and 2). Note, however, that choice of projectile design has a significant effect on the magnitudes of accelerations encountered in the EM system. A comparison of cases 5 and 6 shows that an M829 experiences only one-third the peak transverse acceleration of the Rodman cone projectile when fired from the same EM gun system (cases 1 and 2). Even so, the M829 fired from the SSG is subjected to transverse accelerations five times those encountered in the conventional double-travel gun system (cases 5 and 6 vs. case 7).

Table 2. Calculated Transverse Accelerations

Case	Centerline	Projectile	Velocity-time profile	Transverse Acceleration (g's)					
				Rear Contact			Front Contact		
				1.0×10^5	4.3×10^5	1.0×10^6	1.0×10^5	4.3×10^5	1.0×10^6
1	9/1 rails	Rodman	EM	2,627	9,465	10,960	5,258	9,914	10,024
2	9/16 rails	Rodman	EM	3,430	9,215	22,180	7,233	8,879	7,907
3	9/1 rails	Rodman	Conv	2,697	10,267	8,374	4,983	6,012	3,431
4	9/16 rails	Rodman	Conv	3,557	12,596	8,881	5,538	5,783	3,017
5	9/1 rails	M829	EM	985	2,687	4,772	1,454	3,752	6,687
6	9/16 rails	M829	EM	701	3,162	5,877	1,063	4,001	6,112
7	DT Conv	M829	Conv	534	649	1,491	759	690	1,790

The significant difference in pitching accelerations observed between the two projectiles when fired from the EM gun system appears to be due to the center of gravity (c.g.) of the Rodman cone being located between the boreriders. In contrast, the M829 design has the c.g. located directly beneath the rear contact. This fundamental difference in c.g. location means that any lateral disturbances imparted to the boreriders of the base-pushed Rodman cone will tend to cause it to pitch about its c.g., resulting in increased balloting motion and thus greater projectile/gun interactions. In contrast, in the case of the M829, lateral loadings tend to induce sideways translation rather than balloting motions.

Figures 9 and 10 show the differences in projectile pitching accelerations of the Rodman cone and the M829 between the EM gun system (case 1) and the conventional double-travel gun system (case 7) for the medium spring stiffness value of $k = 4.3 \times 10^5$ lb/in. The magnitude of the peak pitching acceleration for the Rodman cone fired from the EM gun is five times that of the M829 fired from the conventional double-travel gun.

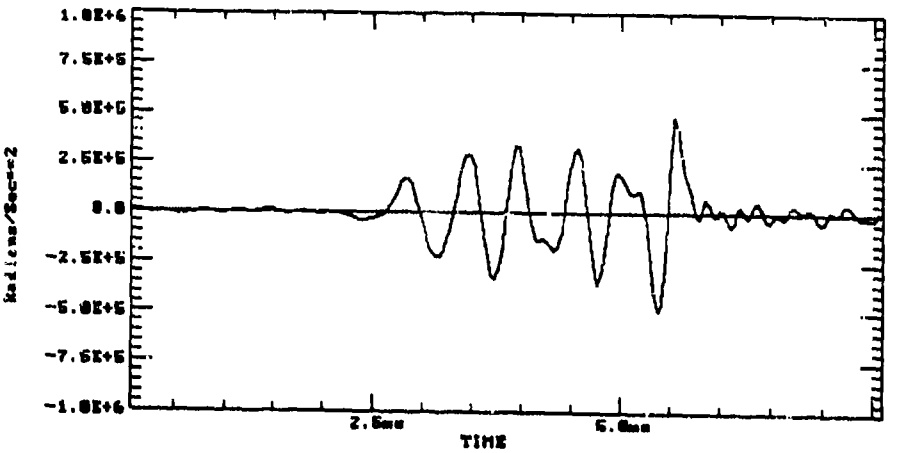

Figure 9. Pitching acceleration vs. time of the Rodman cone projectile in SSG railgun.

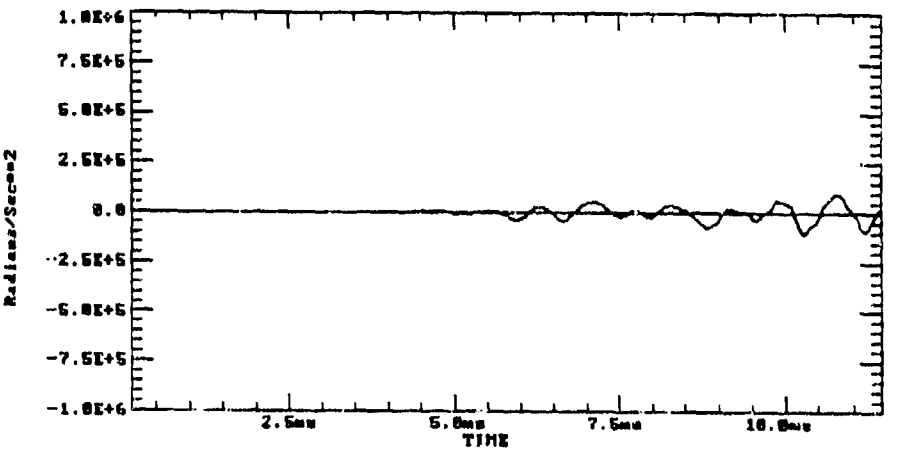

Figure 10. Pitching acceleration vs. time of the M829 projectile in a double-travel conventional tank cannon.

Closer examination of the transverse and pitching acceleration history plots for the EM system showed that the projectile response was consistently initiated between 2.5 and 3.0 ms (see, for example, Figure 9). By integrating the velocity vs. time profile from Figure 3, it was found that after 3.0 ms, the projectile had traveled 2.2 m (87 in). Examination of the rail profile in Figure 4 shows this distance places the

projectile in the region of the kink. Experience with conventional gun tubes has shown that kinked tubes typically result in greater projectile tipoff upon muzzle exit and subsequently such projectiles exhibit poorer accuracy on target (Schmidt et al. 1990). This is particularly true of tubes with kinks near their muzzles where the projectiles have very nearly reached muzzle (ordnance) velocity. On first glance this would appear not to be the case for the SSG, since it has a kink only a quarter of the way along its length. However, at 3.0 ms, the projectile velocity is 1.55 km/s (from Figure 3). Thus, consistent with experience from conventional guns, the kink in the EM rail profile serves to cause significant lateral response of the projectile because the projectile must traverse the kink at a relatively high velocity.

5. CONCLUSIONS

The RASCAL results reported here show the SSG railgun induces significantly greater, an order of magnitude larger, transverse accelerations in projectiles than conventional cannons. This is clearly a result of the kink in the EM rail profile approximately 2 m from the breech end.

The Rodman cone projectile's c.g. location between boreriders also stimulates in-bore response, both lateral and in pitch. This design practice appears to be necessitated by the state-of-the-art of design of plasma armatures which require a base-pushed configuration.

The SSG railgun bore straightness profile problem also has severe consequences for the design of saboted projectiles. The design of such projectiles is constrained by parasitic mass requirements. The design of saboted projectiles can account for more severe lateral loading conditions, but only at the cost of bulking up the structure, thus increasing its mass. This approach obviously results in a reduction of muzzle velocity and moves the design away from useful tactical applications of interest to the Army.

It is likely that even if changes are incorporated in the Rodman cone design to improve structural integrity sufficiently to ensure survival during the launch process, there will still be substantial pitching induced by the poor railgun centerline. This will result in high yaw at muzzle exit and greatly reduce the ability of the projectile to accurately hit a target. Therefore, it is important for the proponents of EM railgun systems for Army use to address the bore straightness issue and immediately undertake steps to ensure straight centerline profiles to reduce or eliminate the lateral loads imparted to projectiles. This will greatly increase the probability of the launch package surviving the launch and accurately hitting a target.

As improvements are made to the fabrication of EM railgun systems, it may be beneficial to adopt some of the more advanced techniques currently in use by the conventional gun projectile designers to examine projectile/gun dynamic interaction. Some of the techniques are listed in the introduction of this report, with the 3-D finite element method lending itself nicely to examining the nonhomogeneous bore cross sections typical of railguns. This method would also be useful in analyzing square bore railguns such as are being pursued in other EM gun programs.

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